A New Grain Harvesting System for Single-Pass Grain Harvest, Biomass Collection, Crop Residue Sizing, and Grain Segregation

M. C. Siemens, D. E. Hulick

ABSTRACT. *A cereal grain harvesting system is introduced that combines existing technologies in a unique way to improve cereal grain harvest performance, increase profitability, and efficiently collect biomass. The harvesting system is comprised of three machines: one to reap grain, harvest biomass, and size crop residue for no-till seeding; a second to thresh and winnow the grain; and a third to separate the grain by quality for added value. This study describes the new harvesting system and the development of one of the system's major components: the reaper/flail harvester. The reaper/flail harvester consists of a mobile power unit, a stripper header to harvest the crop, and a flail to chop the standing residue into small pieces. A prototype harvester was fabricated and tested to determine system design criteria and performance characteristics in terms of machine power requirements, quantity of biomass collected, and bulk density of the material harvested. Trials were conducted in seven wheat (Triticum aestivum L.) fields in Oregon during 2005 and 2006 that ranged in yield from 3.3 to 6.4 t ha^{-1}. Harvester performance was evaluated at various travel speeds, straw chop heights, and with different types of wheat. Flail power requirements were highly linearly correlated with quantity and rate of biomass chopped ($R^2 = 0.91$). The maximum reaping power requirement was 2.7 kW m^{-1}, only slightly higher than the no-load power requirement of 1.9 kW m^{-1}. Power requirements for reaping, conveying, and flailing ranged from a low of 5.0 to a high of 13.5 kW m^{-1} depending on travel speed, crop yield, biomass concentration, and chop height. Values were linearly correlated with the combined grain, chaff, and biomass feed rate (t h^{-1}) with an R^2 of 0.88. Total machine power requirements for a harvester with a 7.3 m header would be about 175 kW, including 75 kW for propulsion, losses, and reserve. Chaff yield in the grain/chaff (graff) mixture harvested exceeded 2 t ha^{-1} in six of the seven trials. With chaff valued at $23 t^{-1}, collecting 2 t ha^{-1} of chaff would increase farm revenues by $46 ha^{-1}. Realistic graff densities of awned wheat were less than 1/11 that of clean grain, and new, efficient material handling systems would need to be developed to have harvesting capacities comparable to that of a conventional combine-based system. Awnless wheat had graff densities that averaged about 1/5 that of clean grain. Equipment is commercially available to handle this volume of material and have harvesting field capacities comparable to that of a conventional combine-based system.*

Keywords. Biomass, Biomass collection, Cereal grain, Chaff, Flail, Harvester, Harvesting system, Power requirement, Reaper, Residue management, Stripper header, Wheat.

Since its introduction in the 1940s, the self-propelled combine has quickly become the predominant method for harvesting cereal grains. Over time, the size, power, and capacity of these machines have increased concomitantly with farm size. Although the modern combine is a highly productive and efficient machine for harvesting and cleaning grain, it is not without its drawbacks. One disadvantage is that their high purchase price of over $250,000 makes the cost of combine ownership significant. Schnitkey and Lattz (2006) estimated that the annual fixed costs (depreciation, interest, housing, and insurance) for owning a small grain combine ranged from $6.40 to $9.00 ha^{-1} depending on combine capacity and farm size. For the majority of growers who manage small farms, fixed costs of this magnitude are cost prohibitive. In an economic analysis of wheat (*Triticum aestivum* L.) harvesting systems, Prentice et al. (1999) found that a combine must be utilized on over 1100 ha before ownership becomes economically viable.

Despite their high cost, the performance of modern combines is found lacking in no-till cropping systems, mainly due to poor crop residue sizing and distribution. Uneven distribution of wheat residues behind the combine leaves windrows of straw and chaff that cause a variety of problems, including poor drill performance, uneven seedling emergence, slower plant growth, lower nutrient availability, an environment favorable to diseases, reduced herbicide

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effectiveness, and increased rodent damage (Allmaras et al., 1985; Veseth et al., 1989; Douglas et al., 1992; Siemens and Wilkins, 2006). Allmaras et al. (1985) suggested that in order to successfully manage residue for no-till seeding after small grain harvest, an uneven residue distribution ratio, defined as the maximum total residue concentration divided by the minimum total residue concentration, of less than 1.5 is required. They found, however, that of 12 combines tested, only one met this criterion. Siemens and Wilkins (2006) evaluated the effect of various wheat residue management methods on no-till drill performance and crop yield. They found that seeding into high concentrations of residue left by non-uniform residue distribution systems resulted in significantly reduced stand establishment and early plant growth, as compared to trials where crop residues were evenly spread and chopped into small pieces. In trials where straw length was left long, drill plugging was problematic. Without tillage, controlling weeds with herbicides is a critical component for successful no-till systems. Since herbicide efficacy can be significantly reduced when surface residues intercept the herbicide (Banks and Robinson, 1982, 1984; Bauman and Ross, 1983; Ghadiri et al., 1984), sizing and managing residue is very important for no-till systems. While the residue handling methods of current harvesting machines may be well suited for tillage-based farming systems, this body of literature suggests that they are not optimal for more sustainable farming systems such as no-till. Alternative harvesting technologies designed specifically for conservation tillage systems are needed to improve the way crop residues are managed.

Another limitation of cereal grain combines is that their design is not conducive to efficient collection of straw and/or chaff for use as a biofuel or as an animal feed. The Prairie Agricultural Machinery Institute (PAMI, 1998) conducted an analysis of various "whole crop" harvesting systems to determine the economic efficiency of harvesting grain, chaff, and straw. Of the five systems examined, the one that would be considered conventional utilized a combine equipped with a cutter-bar header to harvest grain and a dump wagon towed behind the combine to collect chaff. Straw was collected by post-harvest swathing and baling. As compared to alternative systems in which grain and biomass were harvested together and then transported to a stationary thresher for cleaning, the conventional system had the highest cost of operation and provided the least economic return. Although the alternative harvesting systems were the most profitable, only one of the systems, the McLeod Harvest System, is commercially available. The McLeod Harvest System is comprised of two machines rather than a single combine (McLeod, 2007). The first machine is a tractor-pulled harvester equipped with a standard combine cutter-bar header and a unit that partially threshes and separates grain. This harvesting unit gathers small grain, chaff, and weed seeds, but separates out straw, leaving it behind in the field. The "dirty" harvested material is cleaned by the second machine: a stationary threshing/winnowing unit. The manufacturer claims that this system will reduce harvesting equipment costs by 40%, cut grain losses by 2%, produce cleaner grain, remove chaff and nearly all weed seed from the field, and mill valueless docked material into livestock feed (McLeod, 2007). According to Prentice et al. (1999), if these claims were realized on a commercial farm, they would benefit a typical grower $14.80 ha^{-1} each year as compared to conventional combine harvest.

Although the concepts behind this system are promising, further verification and testing is needed, since there is little peer-reviewed literature supporting these claims.

A final drawback of the modern combine is that it does not allow for segregation of grain by quality for added value. All grain harvested by the machine is delivered to a common bulk tank, where grain of varying quality is mixed. Wilkins et al. (1993) demonstrated that test weight and grain protein, two soft white winter wheat grain quality parameters, could be effectively separated by kernel weight using a gravity table. Siemens and Jones (2008) also used a gravity table for segregating soft white wheat and found that overall wheat quality was highly correlated with kernel density (r^2 = 0.88 to 0.94). These findings suggest that there is great potential for segregating grain by density for improved quality and consistency in quality, thereby adding value. Although gravity-table grain processing capacities are too slow to be commercially feasible, fluidized-bed systems with high throughput and low cost could be used. Utilizing such a system on a modern combine would not be feasible without a major redesign of the combine.

In summary, this body of literature shows that new harvesting technologies are needed to lower production costs, improve crop residue management for conservation tillage systems, more efficiently collect biomass, and allow for segregation of grain by quality for added value. The objectives of this project were to introduce a new harvesting system that addresses these issues and to develop one of the system's major components: a reaper/flail harvester. A further objective was to determine the design criteria and performance characteristics of the prototype harvester developed in terms of power requirements, quantity of biomass collected, and bulk density of the material har–vested.

HARVESTING SYSTEM DESCRIPTION

The new harvesting system conceived is comprised of three separate machines: one to reap grain, harvest biomass, and size crop residue for no-till seeding; a second to thresh and winnow the grain; and a third to further clean and separate the grain by quality for added value. The first machine is a reaper/flail harvester comprised of a mobile power unit, a stripper header to gather the crop, and a flail to chop the standing residue into small pieces (fig. 1). A stripper header was selected as the reaping unit since grain and chaff are the two primary materials harvested with this type of header (Wilkins et al., 1996). This limits the volume of material collected as compared to utilizing a conventional cutter-bar header where straw would also be harvested. Collecting chaff for biomass while leaving straw in the field is also more environmentally sound than whole-crop harvesting since chaff has minimal effect on reducing soil erosion and negligible impact on soil nutrients (Stumborg and Townley-Smith, 2004). A flail mower was chosen as the residue sizing device since it has been shown to be an effective residue management tool for no-till cropping systems (Siemens and Wilkins, 2006). In the conceived harvesting system, grain and chaff are conveyed directly to a bulk tank on the mobile power unit without passing through a traditional threshing device (fig. 1). Although the grain and chaff mixture, henceforth referred to as "graff," has 3 to 4
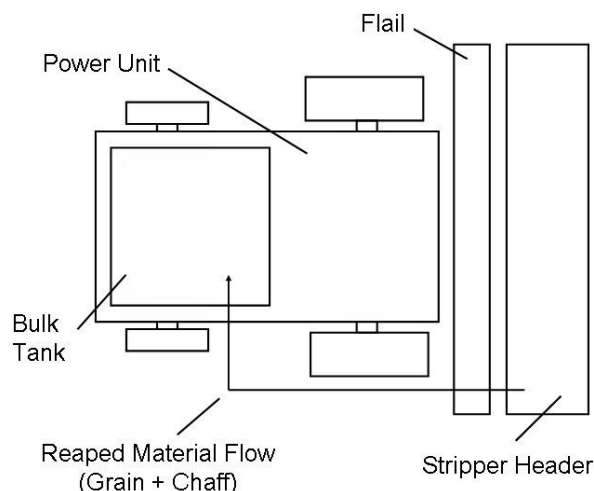
Figure 1. Schematic drawing of a reaper/flail harvester comprised of a mobile power unit, a reaping device (stripper header), and a residue sizing device (flail mower).

times the volume of pure grain (McLeod, 2007), the capacity of the harvester would be comparable to that of a conventional combine by quadrupling the size of the bulk tank. Such a design is feasible since the harvester is not equipped with the space-limiting threshing, cleaning, and separating components of a conventional combine.

The un-threshed graff is hauled to the second machine, a stationary thresher/winnower, where the grain is separated using conventional threshing, separating, and cleaning components found in modern combines. A stationary thresher/winnower has an advantage over a conventional combine in that the separating and cleaning equipment can be sized as large as necessary to minimize grain loss and provide dockage-free grain. In addition, the stationary thresher/winnower is powered by electric motors, which are much more efficient than internal combustion engines at converting energy to useful work. Another advantage is that shrunken kernels, broken kernels, and weed seed are captured and could be used as animal feed rather than returned to the field to proliferate. The chaff stream, which contains 3.5% to 5.5% crude protein and 35% to 45% total digestible nutrients, can also be sold as cattle feed valued at $23 t^{-1} to provide additional farm revenue (Saskatchewan Agriculture and Food, 2000). Chaff would also have value as a cellulosic feedstock for bioenergy, an energy source that has become increasingly important for reducing U.S. dependence on fossil fuels (Hoskinson and Hess, 2004; Kerstetter and Lyons, 2001; Perlack et al., 2005).

Once separated, the clean grain is passed through the third machine in the system, a high-capacity fluidized bed, to further clean and separate the grain by density. These devices are commercially available and capable of processing up to 150 t h^{-1} at a cost of approximately $2.66 ton^{-1} (Camas International, Inc., Pocatello, Idaho, personal communica–tion, 2 Feb. 2002). Because kernel density is highly correlated with grain quality parameters, including protein, test weight, flour yield, and baking quality (Wilkins et al., 1993; Siemens and Jones, 2008), grain of differing quality could be segregated into different storage bins. Segregated wheat would have added value as compared to non-separated wheat and, therefore, presumably command a premium in the

marketplace. Premiums would be used to offset the added handling and storage costs and if high enough, increase farm profits.

The conceived harvesting system significantly reduces harvesting costs by eliminating the need for each harvesting machine to be equipped with expensive threshing and cleaning components. Several simple, low-priced reaping machines could utilize one stationary thresher/winnower and one fluidized-bed system. The grain chaff mixture could be contained in bags similar to those used for storing silage for year round processing. Another advantage of the system is that it properly sizes crop residue for optimum no-till drill performance in a single pass. Costly operations to manage crop residue during or after harvest are not needed. In addition, the system properly sizes and chops crop residue ahead of the unit's tires, which eliminates wheel tracks of trampled residue that are troublesome for no-till drills to effectively seed through. The proposed harvesting unit is self-propelled, but future designs may utilize a reversible tractor to carry and power the header, flail, and conveyor. In such a system, harvested material would be conveyed or blown into a wagon towed behind the harvester. If additional biomass for bioenergy is desired, the flail could be replaced with a sickle-bar cutter or windrower-type header so that straw could be raked and baled or simply baled post-harvest. Because the major components of this system do not currently exist, they will need to be developed and evaluated to determine the feasibility of the system for commercial farming operations. The remainder of this article details the development and evaluation of one of the systems main components: the reaper/flail harvester.

REAPER/FLAIL HARVESTER DESCRIPTION

A prototype reaper/flail harvester was developed utilizing an N-7 Gleaner combine (AGCO Corp., Duluth, Ga.) as the mobile power unit, a 3.7 m wide Shelbourne Reynolds stripper header (Shelbourne Reynolds, Inc., Colby, Kans.) as the reaping device, and a 3.7 m wide Rears Pak-Flail chopper (Rears Manufacturing Co., Eugene, Ore.) equipped with FL940 shredding blades as the residue sizing device (fig. 2). The stripper header, henceforth referred to as the "reaping unit," was equipped with plastic stripping elements for harvesting. A 0.58 m wide slat chain conveyor powered by a hydraulic motor was constructed to deliver the harvested material to the bulk tank. Lift arms were welded to the flail mower and pinned to the mobile power unit's front axle frame to provide a means of supporting the entire reaping unit/flail assembly (fig. 3). A hydraulic cylinder powered lift/tilt mechanism similar to those used on forklifts was fabricated to provide relative vertical and rotational motion between the reaping unit and the flail mower. The combine's original header lift cylinders were attached to the fabricated lift arms and used to lift the entire reaping unit/flail assembly. The original mechanical drive assembly for the reaping unit was replaced with two hydraulic motors to reduce header weight and for ease of assembly. One of the motors had a displacement of 200 cc/rev and was used to power the reaping unit's rotor, while the other motor had a displacement of 77 cc/rev and was used to power the auger. A flow divider was placed in series between the two hydraulic motors to regulate motor speed so that the reaping unit's rotor and auger were
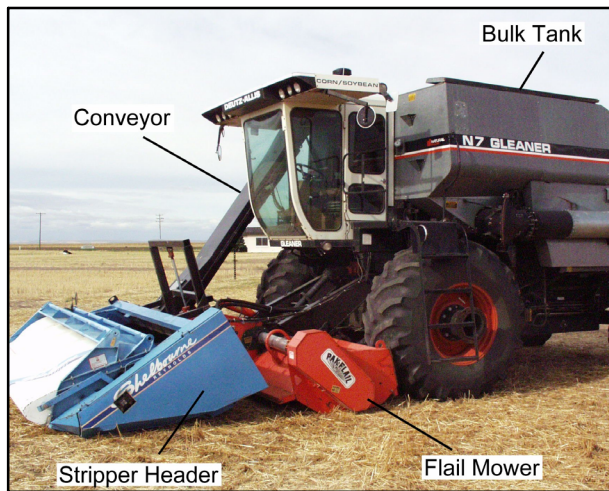
Figure 2. Prototype reaper/flail harvester comprised of an N-7 Gleaner combine as the mobile power unit, a Shelbourne Reynolds stripper header as the reaping device, and a Rears Pak-Flail mower as the residue sizing device.
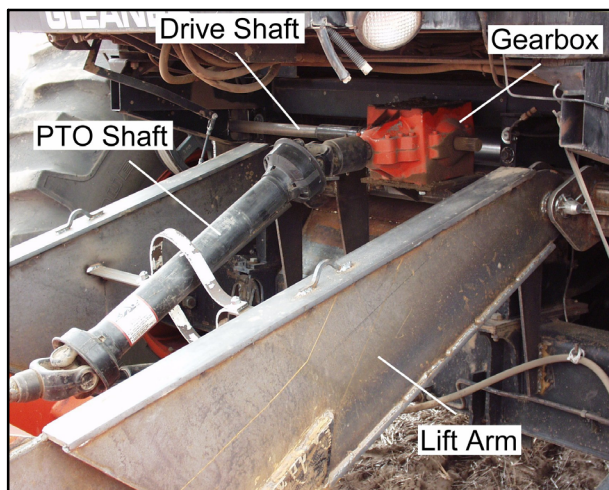

Figure 3. Header lift arm assembly and flail drive train components of prototype reaper/flail harvester.

driven at the manufacturer's recommended wheat harvesting speeds of 600 and 170 rpm, respectively. To supply the estimated 30 kW (8.2 kW m^{-1}) of hydraulic power required by the reaping unit (Shelbourne Reynolds Co., personal communication, Colby, Kansas, 14 March 2002), a 62 cc/rev hydraulic pump was coupled to the combine's original header drive shaft. Flail power was provided by a pair of four sheave pulleys driven by belts connected to the combine's main machine drive shaft. The driven pulley's shaft was coupled to a right-angle gearbox providing via a PTO shaft to the flail (fig. 3). The mechanical drive system was designed to supply the estimated 97 kW (26.5 kW m^{-1} of header width) of power required to operate the flail at 9.7 km h^{-1}.

METHODS

To further the development of the reaper/flail-based harvesting system, design criteria, including system power requirements, quantity of biomass collected, and bulk density of the plant material harvested, were evaluated for the

prototype system developed while harvesting soft white wheat in Oregon in four fields in 2005 and in three fields in 2006. All study sites were located at or near the Columbia Plateau Conservation Research center near Pendleton, Oregon, where the soil is a well-drained Walla Walla silt loam (coarse-silty, mixed, mesic Typic Haploxerolls) and the average annual precipitation is 418 mm. In each year, one of the fields was seeded to an awnless variety of wheat while the remaining sites were seeded to awned varieties of wheat. For the awned wheat field sites, system power requirements, quantity of biomass collected, and graff bulk density data were recorded. For the awnless wheat field sites, only quantity of biomass collected and graff bulk density data were recorded. In 2005, the three fields seeded to awned varieties of wheat were conventionally tilled following a season of fallow, but ranged in expected crop yield and aboveground crop residue biomass due to differences in seeding date and type of wheat grown. One of the fields was seeded to the spring wheat variety Zak, while the other two fields were seeded to Stephens winter wheat at early and late planting dates. The awnless wheat field site was no-till seeded to the variety Brundage96 after a season of fallow. In 2006, the same varieties of awned and awnless wheat were used. Stephens winter wheat was early seeded into a conventionally tilled, summer fallow seedbed, while Zak spring wheat was no-till seeded in a field that had raised winter wheat the previous year. The awnless variety Brundage96 was again no-till seeded into a field that was fallowed the previous year.

To determine system power requirements, each field was laid out in a randomized complete block, split-plot arrangement with three replications in 2005 and two replications in 2006. Main effects were harvester travel speed, while simple effects were flail chop height. In 2005, three harvester travel speeds of 3.2, 5.6 and 8.0 km h^{-1} and three chop heights of 5.1, 20.3, and 35.6 cm were examined. Plot lengths were 13.4, 23.5, and 33.5 m for the 3.2, 5.6, and 8.0 km h^{-1} travel speeds, respectively, to ensure that at least 10 s of power requirement data were recorded for each travel speed. During preliminary trials in 2005, the harvester's conveyor plugged when harvesting high-yielding crops at the high travel speed. Consequently, maximum and mid-level travel speeds in the two winter wheat trials were reduced to 6.4 and 4.8 km h^{-1} respectively. In 2006, travel speeds of 3.2, 4.8, and 6.4 km h^{-1} and flail chop heights of 5.1 and 20.3 cm were investigated for the winter wheat trials. In the spring wheat trials, travel speeds of 1.6, 3.2, and 4.8 km h^{-1} and chop heights of 20.3 and 35.6 cm were examined.

Prior to conducting the experiments, the reaping unit header height and hood position were adjusted to minimize shatter losses. Initially, the header height and hood position were set according to the manufacturer's recommendations for harvesting wheat, with the header height adjusted such that the center of the axle of the harvesting drum was positioned at the top of the wheat plants and the hood oriented such that its top surface was horizontal with the ground surface. During trial runs, the header height and hood position were adjusted until shatter losses were considered minimized based on visual observation. While the optimum header height and hood position varied for each of the seven fields harvested, all trials conducted in a given field were harvested with the same header height and hood settings. It should be noted that despite these efforts, excessive shatter

losses were observed in some fields. These losses were attributed to the later than optimal harvest date and operating the reaping unit at travel speeds lower than those recommended for best harvesting performance (Wilkins et al., 1996). Shatter losses were not measured due to time constraints and because the objectives of this study were to determine system performance in terms of power requirements and bulk density of the material harvested, not harvesting losses.

Four strips of wheat, 70.4 m in length, were harvested with a 2 m wide plot combine prior to conducting the experiments to determine crop yield for each field. Straw yield and total aboveground biomass were also determined by collecting plants cut at ground level and threshing and weighing the sample. The sample area measured 1×0.64 m (3 rows), and 20 samples were collected from random locations in each field. At the end of each reaper/flail harvester pass, the heights of chopped and unchopped straw were measured and recorded. These data were used to determine the quantity (t ha^{-1}) and rate (t h^{-1}) of straw chopped by the flail.

System power requirements measured included those required to reap and convey graff and to flail chop straw. The reaping unit and conveyor were both powered by hydraulic motors, and their power consumption was calculated using the following formula (Goering, 1989, p. 294):

Power consumption (kW) = System pressure (MPa)
$\quad \times$ Flow rate (L min^{-1}) / 60

Each hydraulic motor on the harvester was instrumented with pressure transducers to determine system pressure and an rpm sensor to record motor speed. Fluid flow rate was determined by multiplying motor speed (rpm) by motor displacement (L/rev). Flail power requirements were measured with a torque transducer (model MCRT 49061P(5-3) NNN, S. Himmelstein & Co., Hoffman Estates, Ill.) mounted in-line with the flail drive shaft. All transducer data were recorded on a data logger (model 23X, Campbell Scientific, Inc., Logan, Utah) at 0.1 s intervals. Flail power was linearly regressed with the quantity of straw chopped per unit of time (t h^{-1}), a parameter henceforth referred to as biomass material feed rate. Flow power data collected during the experiment were also compared to values obtained with ASAE Standard D497.4 (*ASAE Standards*, 2003) equations for estimating flail power requirements for flail mowers and for direct-cut flail harvesters. These equations take the following respective forms:

Flail mower power required (kW)
$\quad = 10 \times$ Implement width (m)

Direct-cut flail harvester power required (kW)
$\quad = 10 + 1.1 \times$ Material feed rate (t h^{-1})

The yields in terms of mass (t ha^{-1}) and volume (m^3 ha^{-1}) of the graff harvested were determined by collecting the material in a $1.2 \times 1.2 \times 0.61$ m box placed in the harvester's bulk tank and measuring its volume and weight. This procedure was replicated five times at random locations for each field. Yield and travel speed data were used to calculate the graff material feed rate (t h^{-1}) for each trial. Reaping unit harvesting power requirements were plotted versus graff material feed rate (t h^{-1}), and a linear regression equation was generated. The graff mixture in each box was threshed using an F-Series Gleaner combine to determine reaper/flail grain and chaff yield. Although knowledge of the percentage of wheat threshed by the reaping unit during harvest would be useful data for designing alternative harvesting systems, these data were not recorded in this study due to time constraints. Three samples of chaff from each field were collected and dried to determine average chaff moisture content. Clean grain volume was determined by dividing grain weight by test weight. A graff volume to grain volume ratio was calculated to determine the bulkiness of graff as compared to clean grain.

Because of the time-consuming nature of the experiment, the spring wheat, late seeded winter wheat, and awnless wheat fields were harvested later than the optimum harvest date in 2005. As a consequence, grain shatter losses were much higher than normal and significantly reduced the amount of grain collected by the reaping unit. To obtain a more realistic graff volume to grain volume ratio, the grain volume harvested by the reaper/flail was adjusted to be equivalent to that obtained by the plot combine, and an adjusted graff volume to clean grain volume ratio was calculated. Adjusted and unadjusted values are reported. In 2006, harvest dates were timelier, and the grain yields obtained with the reaper/flail harvester were comparable, but still lower than those obtained with the conventionally equipped plot combine. Lower yields were attributed to excessive shatter loss, again due to operating the reaping unit at travel speeds that were lower than optimal for best performance (Wilkins et al., 1996). Adjusted graff volume to clean grain volume ratios were again calculated and reported separately for the 2006 data so that more realistic conclusions about the harvesting system's viability could be made.

RESULTS

Power requirements for the flail ranged from approximately 2.5 to 10.8 kW m^{-1} of header width, depending on the biomass material feed rate (fig. 4). For the flailing conditions studied in this experiment, when biomass material feed rates were less than about 9.3 t h^{-1}, flail power requirements were lower than the 10 kW m^{-1} $\pm 40\%$ given by ASAE Standard D497.4 for flail mowers (*ASAE Standards*, 2003). This result is understandable since the most common agricultural use of flail mowers is for shredding corn or cotton stalks, where the operating speeds and therefore biomass material feed rates are higher than the feed rates used in this study. In addition, corn and cotton residue may be tougher than wheat straw and therefore require more power to flail chop. Flail power requirements were well correlated with biomass material feed rate (fig. 4). A linear regression fit to the data was highly significant ($P < 0.0001$) and had an R^2 of 0.91. The intercept value of 2.2 kW m^{-1} represents the no-load power requirement and agreed favorably with the measured value of 2.0 kW m^{-1}. Power requirements were generally lower for the spring wheat residue as compared to the winter wheat residue at similar biomass feed rates. Explanations for this might be differences in straw strength between the varieties of wheat grown and/or plant moisture content at the time of flailing. Figure 5 shows a comparison between the measured flail power requirements and those predicted by ASAE Standard D497.4 for direct-cut flail harvesters. For measured power requirements below about 4.0 kW m^{-1}, the ASAE Standard underpredicts the measured power required, while for measured power requirements
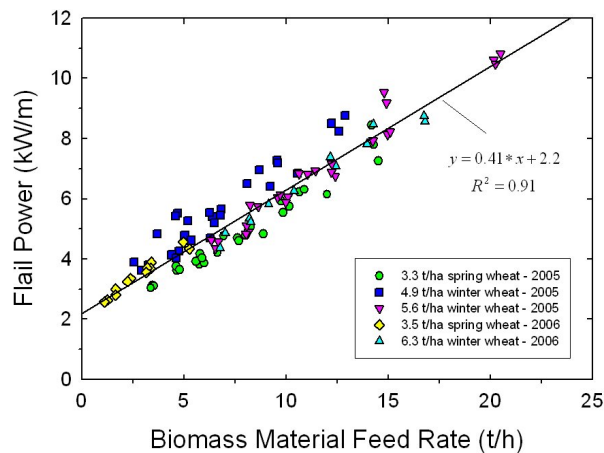
Figure 4. Regression of flail power required to chop winter and spring wheat stubble at various biomass material feed rates during experiments conducted in eastern Oregon in 2005 and 2006.
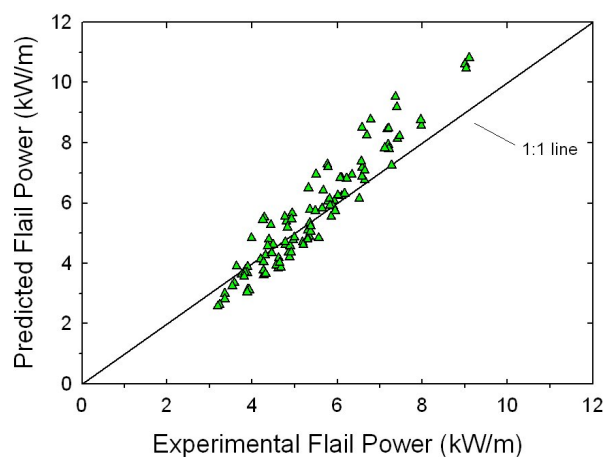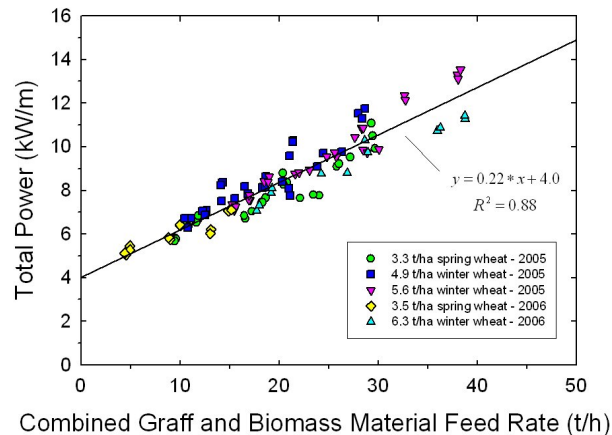

Figure 6. Regression of power required to reap and convey winter and spring wheat graff (grain and chaff) and simultaneously flail chop stubble at various biomass material feed rates during experiments conducted in eastern Oregon in 2005 and 2006.

Figure 5. Comparison of ASAE Standard D497.4 (*ASAE Standards*, 2003) predicted flail power requirements based on biomass material feed rate to measured flail power requirements when chopping winter and spring wheat straw stubble during experiments conducted in eastern Oregon in 2005 and 2006.

above 6.5 kW m^{-1}, the Standard overpredicts the measured power requirement by as much as 2 kW m^{-1}. Even so, the differences between the predicted and measured power requirements were well within the Standard's error range of ± 40%.

Reaping unit power requirement ranged from 2.0 to 2.7 kW m^{-1} depending on graff feed rate and wheat yield. Because these values are only slightly higher than the no-load power requirement of 1.9 kW m^{-1}, the signal to noise ratio was very low, making accurate power requirement data difficult to obtain. Another problem with collecting accurate data was that reaping power requirements for stripping are highly dependent on plant moisture content, and plant moisture content changed dramatically throughout each day while the tests were being conducted. A consequence of this was that although one would expect reaping unit power requirements to be highly correlated with graff feed rate, this was not the case as a linear regression between the two parameters had an R^2 of only 0.14. Maximum conveyor power was 2.2 kW (0.6 kW m^{-1}), also near the no-load value of 1.8 kW (0.5 kW m^{-1}). The 0.4 kW difference between the

maximum power required and no-load power compares favorably with the numerically calculated 0.3 kW of power required to lift the graff mass 6.1 m to the top of the conveyor at the maximum graff feed rate of 17.8 kg s^{-1}.

Total harvester power requirements for stripping, conveying, and flailing ranged from a minimum of 5.0 kW m^{-1} when harvesting 3.5 t ha^{-1} spring wheat at a speed of 1.6 km h^{-1} and chop height of 35.6 cm to a maximum of 13.5 kW m^{-1} when harvesting 5.6 t ha^{-1} winter wheat at 6.4 km h^{-1} and a chop height of 5.1 cm (fig. 6). A harvester with a 7.3 m header and flail would therefore require a maximum of about 100 kW for the conditions tested in this study. Estimating that an additional 75 kW would be required for propulsion, losses, and reserve (Bernhard and Schlotter, 2003), total machine power requirements would be 175 kW. Modern combines designed for 7.3 m headers are typically equipped with 186 kW engines that provide similar amounts of power (Case, 2002). Harvester power requirements were also well correlated with combined graff and biomass feed rate. The linear equation fit to these data had a slope of 0.22, an intercept of 4.0, and an R^2 of 0.88 (fig. 6). Designers can use this equation to predict power requirements for graff and biomass feed rates that are lower or higher than those used in this study.

Graff yield ranged from 4.6 to 9.5 t ha^{-1} for the awned spring and winter wheat crops, and from 4.3 to 8.3 t ha^{-1} for the awnless winter wheat crops (table 1). In 2005, combine grain yields ranged from 3.3 to 6.0 t ha^{-1}, while grain yields harvested with the reaper/flail were 5% to 21% lower. This result was not unexpected. For the type of header used on the reaper/flail harvester, Wilkins et al. (1996) found that shatter losses ranged from 5% to 23% when travel speeds were less than 3.7 km h^{-1}, and a third of the trials in this study were conducted at speeds below 3.7 km h^{-1}. An exception was the awnless winter wheat trial in 2005, where harvesting losses were 53%. In this case, the crop was harvested more than a month and a half after the optimum harvest date and was therefore very prone to shatter loss. In 2006, grain yields with the reaper/flail were again lower by 1.5% to 14% than those obtained with the conventional combine. These reduced yields were also within the range expected considering the lower than optimal travel speeds used during the study. Although combine grain yields ranged from 3.3 to 6.4 t ha^{-1},

Table 1. Yield and volume of grain, chaff, and grain mixed with chaff (graff), and ratios of graff volume to grain volume of wheat harvested by conventional combine and reaper/flail-based harvester in eastern Oregon in 2005 and 2006.

Sowing Date	Wheat Type	Combine		Reaper							
		Grain Yield[a] (t ha-1)	Grain Vol. (m3 ha-1)	Grain Yield[a] (t ha-1)	Grain Vol. (m3 ha-1)	Chaff Yield[b] (t ha-1)	Graff Yield[c] (t ha-1)	Graff Vol. (m3 ha-1)	Graff Vol./ Grain Vol. (ratio)	Grain Vol. Adj.[d] (m3 ha-1)	Graff Vol./ Grain Vol. Adj.[d] (ratio)
2005											
Spring	Awned	3.3	4.3	2.6	3.3	2.0	4.6	76	23.0	4.3	17.7
Winter-late	Awned	4.9	6.3	4.1	5.1	2.3	6.2	94	18.4	6.3	14.9
Winter-early	Awned	5.6	7.2	5.3	6.6	2.5	7.6	89	13.5	7.2	12.4
Winter-early	Awnless	6.0	7.8	2.8	3.5	1.6	4.3	31	8.9	7.8	4.0
2006											
Spring	Awned	3.5	4.5	3.0	3.8	2.3	5.3	94	24.7	4.5	20.9
Winter-early	Awned	6.3	8.1	6.2	7.8	3.5	9.5	93	11.9	8.1	11.5
Winter-early	Awnless	6.4	8.4	6.0	7.6	2.5	8.3	50	6.6	8.4	6.0

[a] Grain yield adjusted to 10% moisture content (d.b.).
[b] Yield reported on a dry tons per hectare basis.
[c] Yield reported on a wet tons per hectare basis.
[d] Due to excess shatter losses, grain volume harvested with reaper adjusted to the grain volume obtained when harvesting an equivalent area with a conventional combine.

chaff yield was fairly consistent, ranging from 2.0 to 2.5 dry t ha-1 in five of the seven trials. In six of the seven trials, chaff yield exceeded 2.0 t ha-1. The one exception was the awnless winter wheat trial in 2005, where reaper grain yield was 53% lower than combine yield, and consequently reaper chaff yield was also low at 1.6 t ha-1. It is reasonable to assume that if the reaper/flail harvester had harvested a quantity of grain equivalent to that of the conventional combine, chaff yield would have also increased and likely doubled to 3.2 t ha-1. Based on these results, it was concluded that at least 2 t ha-1 of biomass can be harvested using the reaper/flail harvesting system when wheat yields exceed 3.3 t ha-1. With chaff valued at $23 t-1 (Saskatchewan Agriculture and Food, 2000), collecting 2 t ha-1 of chaff would increase farm revenues by $46 ha-1. Although the amount of residue that can be sustainably removed depends on many factors and is not an exact science, most researchers would agree that removing 2 t ha-1 of chaff is sustainable as long as 3.4 to 5.6 ha-1 of crop residue is retained in the field annually (Rasmussen et al., 1980; Kerstetter and Lyons, 2001; Perlack et al., 2005).

Graff volume was excessively high for the awned wheat varieties, ranging from 76 to 94 m3 ha-1 (table 1). As compared to the volume of grain harvested from an equivalent area, these volumes were 11.9 to 24.7 times greater than the volumes of clean grain harvested from an equivalent area. A practical consequence of this result is that the bulk tank of the reaper/flail harvester would need to be more than 11.9 times larger than that of a conventional combine in order to harvest an equivalent area before unloading. For the awnless wheat crops, the ratios of graff volume to clean grain volume were 8.9 and 6.6 in 2005 and in 2006, respectively. Although these values were significantly lower than those obtained for awned wheat crops, having to handle up to 8.9 times more volume than that of clean grain limits the commercial feasibility of a reaper/flail-based harvest system. These results were not expected, since McLeod Harvest Inc. (McLeod, 2007) reported that graff volumes were only 3 to 4 times that of clean grain. One reason for these differences is that the graff harvested by the McLeod system is threshed, and therefore wheat plant materials are crushed and broken. When graff is harvested

with a reaping unit and conveyed directly to the bulk tank, awns and other wheat head plant material remain mostly intact. Unbroken awns tended to bridge in the graff material collected, causing bulk densities to be low. This phenomenon also helps explain why graff volumes of awned varieties of wheat were much higher than those of awnless varieties. A second explanation for the high graff volume to clean grain volume ratios found is that the volume of grain in the graff collected was artificially low due to excessive shatter loss. When reaper/flail harvester grain volumes were adjusted to reflect those obtained with the combine, graff to grain volume ratios for awned wheat varieties were significantly reduced, ranging in value from 11.5 to 20.9. Although these values represent more realistic graff to grain volume ratios, handling over 11.5 times more material than clean grain is not practical for commercial farming operations. Additional equipment and systems for increasing graff density through compression or by size reduction would be required to make this system commercially feasible. Using awnless varieties exclusively may provide a viable alternative to developing such equipment. When clean grain volume was adjusted to more accurately reflect true crop yield, awnless winter wheat graff to grain volume ratios were reduced to 4.0 and 6.0 for crop years 2005 and 2006, respectively. For the two years studied, the average graff to grain volume ratio was 5.0, which compares more favorably with the 3 to 4 graff to grain volume ratio reported for the McLeod system. The McLeod system utilizes oversized bulk tanks on the harvester, semi trucks for transportation, and large hoppers for the stationary thresher/winnower to have harvesting capacities comparable to that of a conventional combine (McLeod, 2003). This equipment may be able to be utilized and adapted to the system proposed in this article so that its harvesting capacity is also feasible for commercial farming operations.

CONCLUSION

A new harvesting system comprised of three separate machines (one to reap grain, harvest biomass, and size crop residue for no-till seeding; a second to thresh and winnow the grain; and a third to further clean the grain and separate it by

density/quality for added value) was introduced. The first of these machines, a reaper/flail harvester, was developed and tested. The prototype harvester utilizes a stripper header as the reaping device and a flail mower as the residue sizing device. The power requirements of the prototype harvester were evaluated when harvesting spring and winter wheat crops that ranged in crop yield from 3.3 to 6.0 t ha^{-1} in 2005 and from 3.5 to 6.4 t ha^{-1} in 2006. Flail power requirements ranged from 2.5 to 10.8 kW m^{-1} depending on harvesting speed, concentration of biomass, and chop height. Flail power requirements were linearly correlated with biomass feed rate (t h^{-1}) with an R^2 of 0.91. Because flail power requirement was highly correlated with biomass feed rate, ASAE Standard D497.4, which estimates flail mower power requirements strictly as a function of implement width, should be revised to account for variations in biomass feed rate to improve its prediction accuracy. Reaping unit power requirements ranged from 2.0 to 2.7 kW m^{-1} depending graff feed rate (t h^{-1}). Because these values are only slightly higher than the no-load power requirement of 1.9 kW m^{-1}, accurate reaping unit power requirement data were difficult to obtain. Another problem with collecting accurate data was that plant moisture content has a large affect on reaping unit power requirements, and plant moisture content varied dramatically during the testing period. As a consequence, an unexpectedly poor relationship between reaping unit power requirements and graff feed rate (t h^{-1}) was found (R^2 = 0.14). Maximum conveyor power requirement was 2.2 kW (0.6 kW m^{-1}), also near the no-load value of 1.8 kW (0.5 kW m^{-1}). Harvester power requirements for harvesting, conveying, and flailing ranged in value from 5.7 to 13.5 kW m^{-1} and were highly linearly correlated with combined graff and biomass feed rate (R^2 = 0.88). For the regionally typical conditions tested in this study, a harvester with a 7.3 m wide header and flail would require a maximum of about 100 kW of power. Total machine power requirements would be 175 kW, including 75 kW for propulsion, losses, and reserve. Modern combines designed for 7.3 m platforms are typically equipped with 186 kW engines that provide similar amounts of power. Equipment designers can use the regression equation gen–erated to predict power requirements for lower or higher graff and biomass feed rates than those used in this study.

Although grain and graff yields ranged from 3.3 to 6.4 t ha^{-1} and from 4.3 to 9.5 t ha^{-1} respectively, chaff yield was fairly consistent, ranging from 2.0 to 2.5 dry t ha^{-1} in five of the seven trials. In six of the seven trials, chaff yield exceeded 2.0 t ha^{-1}. Collecting 2 t h^{-1} of chaff would increase farm revenues by $46 ha^{-1} with chaff valued at $23 t^{-1}. Graff volume was excessively high for the awned wheat crops, ranging from 11.9 to 24.7 times greater than the volume of clean grain harvested from an equivalent area. Material bridging caused by intact awns and artificially low volumes of grain in the graff collected were reasons why graff density was so low. When grain volumes were adjusted to reflect true grain yield, graff to grain volume ratios ranged from 11.5 to 20.9. Even though this adjustment increased graff densities to more realistic values, a practical consequence of this result is that the bulk tank of the reaper/flail harvester would need to be more than 11.5 times larger than that of a conventional combine to be able to harvest an equivalent area before unloading. In order to make this harvesting system practical for commercial farming operations and have harvesting capacity similar to that of a conventional combine, equipment would need to be developed to increase the bulk density of graff through compression or by size reduction through means such as additional threshing. An alternative would be to develop new, high-capacity material handling systems. Raising and harvesting awnless varieties of wheat exclusively may provide a viable option to developing such equipment. Adjusted awnless graff volumes were 4.0 and 6.0 times the volume of clean grain for crop years 2005 and 2006, respectively. A harvest system that collects graff with densities approximately 1/3 to 1/4 that of clean grain is currently commercially available. Material handling equipment used for this system may be able to be adapted to the harvesting system proposed in this article to provide harvesting capacities comparable to that of a conventional combine.

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